Semi-Annual Report
for

VACUUM TEST OF INSTRUMENT SIZE GEARS

(22 June, 1965 - 1 January, 1966)

Contract No. NAS5-9590

Prepared by

IIT Research Institute
Chicago, Illinois

for

NASA
Goddard Space Flight Center
Greenbelt, Maryland

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By

Shapoor Guzder

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PREFACE

This program was conducted for the NASA Goddard Space Flight Center, with Mr. Charles E. Vest as NASA's Technical Officer. At IIT Research Institute, the program was directed by Frank Iwatsuki, Manager, Fluid Systems and Lubrication and Shapoor Guzder, Project Engineer. Other IIT Research Institute personnel who have contributed to the technical efforts of the project are T. L. Bush and R. Pape.

VACUUM TEST OF INSTRUMENT SIZE GEARS

ABSTRACT

This report describes in detail the experimental facilities and test procedures which have been developed for evaluating instrument size gears for their reliability and suitability for space application. Two separate test apparatus have been designed and constructed for testing two hundred and twenty-four (224) instrument size fine pitch gears of eight (8) different gear materials in vacuum and laboratory atmosphere. Detail descriptions are given of the four-square gear test rigs, master gear arrangement for monitoring the rate of wear, and instrumentation pertaining to measurements of other testing parameters.

Based on the results of preliminary tests, it can be concluded that the test apparatus and instrumentation have adequate precision and resolution for performing gear wear tests with desired accuracy.

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VACUUM TEST OF INSTRUMENT SIZE GEARS

I. INTRODUCTION

This report summarizes the work performed on the subject contract during the period of June 22, 1965 to January 1, 1966. The objective of this program is to evaluate two hundred and twenty-four (224) instrument size gears to determine their reliability and suitability for space application. The true significance of this program is in the meaning associated with the terms reliability and suitability. Quite obviously, for the specific selection of gear materials to be tested, one of the most important purposes of this program is to obtain significant experimental data pertaining to gear failure and wear rates and tooth surface degenerations. All gears are tested using four-square gear testers at a speed of 1800 rpm under a torque of 20 oz-in. Each test shall continue until the gear tooth profile has been reduced by approximately 10% or until 720 hours of continuous operation have elapsed. For every gear material combination the evaluation will include triplicate runs under vacuum and one run in atmosphere under a dust cover.

Up until now, the principal effort has been devoted towards the design and construction of the test facilities and instrumentation. This report also includes the results of some preliminary runs that have been made to gain insight as to the following test procedures. The remaining period of this program will be devoted to gear testing and post test analysis.

II. GEARS AND GEAR MATERIALS

A. Gear Selection

Gears can generally be identified as power or instrument type. Coarse-pitch gears with high load carrying capacity requiring lubrication are usually referred to as power type, whereas fine pitch gears requiring some periodic lubrication or none at all are considered instrument type gears.

Since the primary purpose of this testing program is to determine finite load-life relations of different gear materials with minimum data scatter, it was decided that all gears shall be of instrument type and would be tested without any lubrication. Precision spur type gears of involute tooth geometry have been selected for these tests because precision, miniaturization and load carrying capacity are important considerations for space application.

B. Gear Specifications

All test gears and master gears are manufactured as per the following specifications defined by AGMA for 20° pressure angle fine pitch gears of involute tooth geometry:

1. Test Gears

Diametral Pitch	-	48
Pressure Angle	-	20°
AGMA Classification	-	#12 Quality
Tooth-to-Tooth Composite Tolerance	-	.0003"
Total Composite Tolerance	-	.0005"

Backlash	-	Designation "D" (Backlash per mesh of .0003" to .001")	
No. of Teeth		55	56
Face Width		.187" $\pm$ .005	.125" $\pm$ .005
Pitch Diameter		1.1458 + .0000 - .0007	1.1667 + .0000 - .0007

2. <u>Master Gears</u>

Diametral Pitch	-	48
Pressure Angle	-	20°
AGMA Classification	-	#14 Quality
Tooth-to-Tooth Composite Tolerance	-	.00014"
Total Composite Tolerance	-	.00027"
Backlash	-	Designation "E" (Backlash per mesh of .0 to .0005")
No. of teeth	-	56
Face Width	-	.110 $\pm$ .005
Pitch Diameter	-	1.1667 + .0000 - .0005
Material	-	Stainless Steel #416 Hardened to RC 55-60

C. <u>Gear Materials</u>

It is known that no adequate prediction of wear rates of materials can be made using presently available theories, even under normal atmospheric conditions. The complications of gear geometry, vacuum, and unknown equilibrium temperatures makes quantitative prediction of gear wear rates in vacua virtually impossible. Qualitative and comparative estimates can, however, be made with much better success and accuracy using results of well planned experiments. In addition to the various unpredictable influencing factors, the gear material is very largely responsible for gear life. For vacuum application, materials of composite nature incorporating solid lubricants have been used in the past with some success. Application of dry film lubricants has been incorporated also. At times it has been proven advantageous to mate gears of two different materials; however, under those circumstances the results would indicate wear rates for not just one material, but would refer to that particular material combination.

In this gear test program, the following materials and material combinations have been specified for the test gears:

1. <u>Materials</u>

   I. Carburized C1020 Steel - Case Depth (0.002" - 0.003")

   II. Nitrided Nitralloy 135 Mod Steel - Case Depth (0.002" - 0.003")

   III. Sintered Aluminum Powder (SAP)

   IV. 7075 Al Alloy Deep Anodized (Martin Hard Coated) - Case Depth (0.002" - 0.003")

   V. 440CSS Heat Treated to RC 55-60

   VI. Phosphor Bronze - 15% MoS_2 Matrix Material

   VII. C1085 (Heat Treated to RC 50) Silver Plated 0.0001" with .0001" of E_3C Molykote Film (MoS_2 Film - Alpha Molykote Corp.)

   VIII. 7075 Al Alloy Light Anodized

2. <u>Material Combinations</u>

Every test gear will be evaluated against another test gear of a different material, and for every material combination one run will be made in laboratory atmosphere and three runs in vacuum.

Following are the various combinations of materials that will be evaluated:

Material	Vs	Material
I		II
II		III
II		IV
II		V
II		VI

Material	Vs	Material
II		VII
III		IV
III		VI
III		VIII
IV		VI
IV		VII
IV		VIII
V		VI
V		VII

It should be noted that the above tabulation contains fourteen (14) different material combinations and eight (8) gears of each material will be evaluated per combination.

D. Gears and Materials Procurement

1. Procurement of Gears

Initial investigations on the manufacturing procedures of precision gears of AGMA #12 quality, especially of the materials specified in the subject contract had clearly indicated that gears of all materials except those of Material VI (Phosphor Bronze - 15% MoS_2 Matrix Material) and Material III(SAP) would definitely require finish grinding after the necessary heat treatments and surface treatments. This caused substantial difficulty and delay in locating manufactures that have the facilities for finish grinding such fine pitch precision instrument gears. We have procured gears of all materials except III, IV & VI. The gear manufacturer is having some difficulty with Material IV (Martin Hard Coated 7075 Al Alloy) in regards to obtaining uniform case depth on the teeth profile.

2. Material Procurement

Procurement of only Materials III & VI will be discussed here as the other materials were readily available. Initial survey and investigation leading to manufacturers of powdered metals indicated that both these materials are not commercially available. Manufacturing of these materials is apparently a state-of-the-art and familiar to only a few of the research organizations. This, again, posed considerable difficulty in locating the sources. However, we were able to acquire samples of these materials and these samples were analyzed here to determine some of the physical properties and material composition. Following is a brief discussion on the analysis of the tests conducted on samples of Material VI (Phosphor Bronze - 15% MoS_2 Matrix Material) that were prepared for us by SKC Research Associates on the best trial basis to achieve as high as 15% MoS_2 impregnation.

Based on the assumption that the Phosphor bronze used in the samples contained 8% Tin and 15% MoS_2 by weight, the theoretical density can be calculated to be approximately 7.82 grams/cc. whereas the actual density measured was 5.7 grams/cc. for one sample and 6.1 grams/cc. for another. This indicates that the specimens were approximately 75.5% dense or 24.5% porous.

Chemical analysis of the specimens showed that the Molybdenum content was approximately 6.90% by weight. Again the theoretical Molybdenum content based on the assumption of 15% MoS_2 in the specimen should be approximately 11.2%. This indicates that these specimens were impregnated to only 9.25% MoS_2.

Another interesting evaluation was the modulus of rupture based on bend strength measurements. The specimen with density of 5.7 grams/cc. had modulus of rupture of 7,260 psi whereas the specimen with density of 6.1 grams/cc. had modulus of rupture of 11,538 psi. It is indicative that much higher strength can be achieved by increasing the density of the specimens. There are no commercial materials of this composition available with which these test results can be compared. However, it is interesting to note that

Sintered Bronze bearing materials of close to theoretical density are known to have modulus of rupture from 25,000 psi to 35,000 psi.

Figure 1 (magnification X 100) shows the microstructure of one of the samples. The specimen was diamond polished and unetched. The porosity of the material can be easily seen here. All the gray areas indicate presence of MoS_2 and the black areas either indicate pores or places where MoS2 was pulled out during polishing process. No attempt was made to estimate the MoS_2 content from the microstructure study; however, the photograph shows a fairly good distribution of MoS_2.

Based on the results of these tests, we have requested the manufacturer to make gear blanks with higher density and higher MoS_2 content.

Samples of Material III (SAP) were also tested for strength and presence of oxide content. Their density was close to the theoretical density. However, the samples were lacking in sufficient presence of Al oxide content. Subsequently, the manufacturer is trying to make gear blanks from Al powder of higher oxide content.

III. TEST FACILITY

A. Preliminary Design Considerations

The first and a major phase of this program was to design and construct a test facility for evaluating the gears under vacuum environment and also in laboratory atmosphere under dust cover. There were several factors to be considered in designing the test facility. However, since the number of gears and gear material combinations to be tested were already specified, the initial task was to consider the appropriate test fixture design which would enable completion of all the tests within the alloted test period. Considering that there are two hundred and twenty-four (224) gears to be tested and there are a total of fourteen (14) different material combinations to be evaluated, it was felt that a test facility capable of testing 32 gears of two different material combinations simultaneously would be adequate for completing the entire test program in a maximum period of seven (7) months based on the requirement that each test would be conducted for a maximum of seven hundred and twenty (720) hours. This period does not include the change over and set-up time between tests.

Since the subject contract calls for testing of all gears under constant load and speed conditions, a four-square gear testing configuration was selected. The utilization of the four-square arrangement is considered ideal for testing gears in a vacuum environment. It permits operation of the gears under desired loads without imposing strenuous requirements on mechanical vacuum chamber penetrations. A total of eight four-square testers would be required to test thirty-two gears simultaneously, six of which have been included in the design of the test facility for vacuum conditions and the remaining two would be used for testing gears in laboratory atmosphere under a dust cover.

Two separate apparatus have been designed. One for testing gears in laboratory atmosphere and the other for vacuum environment as shown in Figures 2 and 3 respectively. In addition to the four-square test rigs and drive motors, each apparatus includes a master gear mechanism, the function of which shall be discussed later in this section. It should be noted that all four-square test rigs in both apparatus are positioned around this master gear mechanism such that all test gears are at the same radial distance from a vertical reference center line which coincides precisely with the center line of the rotation of master gear mechanism.

B. Four-Square Test Rig

Each four-square test rig basically consists of one drive shaft coupled to the drive motor through a magnetic coupling on which two gears of the same number of teeth (55 teeth) are mounted mating with two other gears (of 56 teeth) mounted on separate shafts but coupled through a torque spring. This torque spring determines the amount of loading on the gears. Due to the twisting nature of the torque spring, the diagonally opposite pairs of gears in the four-square arrangement become drivers and driven respectively. Figures 4 and 5 show the gears and bearing arrangements of a four-square rig. The construction of each rig consists of four precision bearing blocks mounted on a vertical base plate. The two smaller bearing blocks each containing only one bearing, support the main drive shaft on which two test gears of 55 teeth are mounted. These bearings are axially loaded through the gears and sleeve arrangement by a fine-threaded sleeve shown between the gears. The other two larger bearing blocks each consisting of two bearings support the two separate shafts on which the other two gears of 56 teeth are mounted respectively. These shafts are in turn coupled by the torque spring shown between the gears. The bearings are axially loaded by the fine threaded nuts shown on the outer end of the shafts. The bearings used in the rigs are of the R-4 size and are of precision quality with retainers of Salox "M" material. This retainer material has been specially selected to provide some lubrication to the balls and the races of the bearing. The main drive shaft on the rig is coupled to the shaft containing the driven magnet of the magnetic coupling by a flexible torsional coupling, the purpose of which will be discussed later. The shaft containing the magnet is supported by two other bearings contained in the horizontal base plate. The other magnet is directly mounted on the drive motor shaft which is mounted under the base plate. Precision and fine tolerance have been maintained in the construction of all the parts to provide adequate accuracy and alignment. Provision is made for fine adjustments on the center distance of the shafts to accommodate variations in the pitch diameters of the mating pair of gears. Although Figures 4 and 5 show the test rig arrangement for the apparatus used for testing gears in laboratory atmosphere, the same design holds for the four-square rigs used in vacuum environment as indicated in Figure 3.

C. Master Gear Arrangement

The test facility also incorporates the use of a spring loaded master gear arrangement. This arrangement will be used periodically to monitor the wear rate on the test gears. The master gear technique has been utilized by most gear manufacturers in determining the precision of the gears. The arrangement basically consists of a spring loaded ultra-precision master gear mating with a test gear. On revolving the combination and precisely measuring the variations in the center distance between the master gear and the test gear, accurate measurements of Tooth-To-Tooth Composite Tolerance* (referred to hereafter as TCE measurements) and Total Composite Tolerance** can be made. As shown in Figure 6 the master gear is mounted in a U-shaped bracket precisely sliding

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* Tooth-To-Tooth Composite Tolerance is defined as the allowable variation in center distance when a gear is rotated (in tight mesh with a master gear) through any increment of 360°/N (N = number of teeth in gear under inspection).

** Total Composite Tolerance is defined as the allowable variation in center distance when a gear is rotated (in tight mesh with a master gear) one complete revolution (This includes the effects of variations in active profile, lead, pitch, tooth thickness and run-out).

and spring loaded within another rotary bracket which can be moved vertically and also revolved to bring the master gear into contact with any of the test gears. While mating with a slowly revolving test gear, the variations in the center distance are measured by a linear variable displacement transducer (LVDT) which senses the movements of the U-shaped bracket supporting the master gear. The purpose of this arrangement is, therefore, two-fold: (1) to make periodic TCE measurements, and (2) to determine the amount of wear on the tooth profile by measuring changes in the center distance between the master gear and the test gear. Figure 3 shows the master gear arrangement to accommodate periodic testing of all the test gears within the vacuum chamber. Here, the arrangement consists of two separate master gears with individual LVDT's mounted on a rotary fixture which is driven inside the chamber by a rotary feedthrough mechanism. A precision indexing arrangement is also provided on the master gear mechanism such that the master gear can be accurately indexed for repeated tests against each test gear.

D. Vacuum System

Of all the space environmental parameters affecting the operation of mechanical components, the "hard vacuum" is by far the most influential. Reproduction of the exact density, molecular flux and composition of the environment is not essential for meaningful tests if the fundamental interactions can be predicted. In order to reduce the interaction of mechanical wear surfaces with the impinging gas species to a negligible level, it is required to reduce the molecular flux to a level at which the monolayer adsorption is very long compared to the time for one revolution of a gear. Thus, for a gear speed of 1800 rpm, a chamber pressure of 5×10^{-8} or less would provide adequate simulation.

The complete vacuum test facility consists of:

1. Test apparatus with a provision of a maximum of eight four-square test rigs
2. 14" dia. and 12" high stainless steel vacuum chamber with four view ports, one 14" Wheeler flange, three electrical feedthroughs, one mechanical rotary feedthrough and a 6" pump manifold with two roughing valves
3. Two Varian Vac Sorb roughing pumps
4. Varian water cooled titanium sublimation pump
5. One 500 l/s Vac Ion pump

IV. TEST PROCEDURES AND INSTRUMENTATION

In this section the test procedures, including specimen preparation and instrumentation will be covered in further detail. As specified in the subject contract, all tests will be continued until the gear tooth profile has been reduced by approximately 10% or until 720 hours of continuous operation have elapsed. In the four-square test rigs, where the direction of rotation is not reversed, the wear will take place on only one surface of each tooth. Therefore, considering 10% reduction in the width of a tooth at pitch circle, the test fixture should be capable of measuring changes in the tooth width (for 48 pitch) from 0.0000 to 0.0032 quite precisely. Besides this, there will be other measurements made, either periodically or continuously during testing. Several measurements will also be made during assembly of component parts to assure perfect alignment and backlash between mating gears.

A. Measurements During Assembly

1. Photographic Records

Photographic coverage of the condition of every gear before evaluation shall be made. This record shall consist of a typical tooth profile (three or more adjacent teeth) of each gear before test.

2. Alignment Checks

Several checks using dial indicators will be made during assembly of test rigs to assure perfect alignment and parallelism of all shafts.

3. TCE Recordings

Using master gear arrangements all gears will be checked for Tooth-To-Tooth error and Total Composite errors. As explained earlier, this will be accomplished by mating master against test gears and recording the output of the LVDT on a recorder while the test gear is rotated slowly through one complete revolution. If these recordings do not conform to those supplied by the gear manufacturer, it will indicate that either the gears were damaged in shipment or handling, or there is some error in the test fixture or instrumentation.

4. Center Distance Adjustment

Center distances between the mating gears will be adjusted accurately to provide the specified backlash. The theoretical pitch diameters and actual variations in tooth width and pitch diameters as seen on the TCE charts will be taken into consideration in determining the required center distance.

5. Positioning Test Gears

The adjustment of the position of all the test gears on the test rig in the apparatus for vacuum testing is quite important. As was mentioned earlier there are two master gears provided in the test fixture for TCE measurements. These master gears have to mate with all the test gears precisely, and since there is no vertical positioning adjustment provided on the master gears, all the test gears corresponding to the mating master gear would have to be located in one horizontal plane within a tolerance of $\pm$ .002 of each other.

6. Bearing Check-Out

During assembly, coast-down measurements will be made on the test rigs with zero load on the test gears for determining that the bearings are operating freely. These coast-down measurements will be made by speeding up the four-square rig to a certain rpm and then decoupling the magnetic drive at a specified rpm and accurately measuring the time the test rig takes to coast down to zero rpm.

7. Torque Measurements

In addition to the coast down tests mentioned above, measurements of torque input to the rig with and without any load on the gears will also be made. The torque input to the test rigs will be measured with the use of a flexible coupling provided between the main shaft of the four-square rig and the input shaft containing one of the magnets (see Figure 4). A magnetic pickup used in conjunction with this flexible coupling measures the angular deflection between the two ends of the coupling which is proportional to the input torque to the test rig at any rpm. Knowing the deflection rate of the spring in the flexible coupling, the angle of deflection measured at any rpm can be easily translated to the actual torque input to the test rig.

8. Motor Current

The armature current of the DC drive motors will be checked under no load and full load conditions during assembly to determine the condition of the motors before initiating the tests.

9. Gear Loading

The test gears in the four-square test rigs will be accurately loaded to 20 in.-oz. by twisting the torque spring between the test gears using a torque wrench. These torque springs have a deflection rate of approximately five degrees per in.-oz. of torque and therefore any change in the deflection of the torque spring due to wear on the gear teeth will not make any significant change in the pre-set torque.

B. Measurements During Testing

1. Continuous Measurements

The armature currents of the DC drive motors will be continuously monitored on a multipoint recorder. Since the armature current of the permanent magnet DC motors is directly proportional to the torque output of the motors, this monitoring will provide a continuous record of the torque input to the test rigs.

2. Periodic Measurements

a. Using the master gear, periodic measurements of the changes in the center distance between each test gear and the master gear will be made to determine the percentage reduction in the tooth profile of the test gears. The tests will be terminated when the change in the center distance exceeds .0046 on any one of the test gears in a four-square test rig. This variation in the center distance corresponds to the 10% wear on the tooth profile of the test gear at the pitch circle.

b. TCE measurements will also be made periodically using the master gear.

c. In addition to monitoring of the DC drive motor current, periodic torque input measurements will be made using either the flexible torque coupling with magnetic pickup arrangement or by the coast-down technique.

C. Measurements After the Completion of Test

1. Photographic Records

Photographic coverage of the condition of every test gear after termination of the test shall be made. This record shall consist of a typical tooth profile (three or more adjacent teeth) of each gear after test.

2. Wear Debris Measurement

Attempt will be made to collect all the wear debris from each pair of test gears in trays mounted under the gears during the test. After termination of the test, a quantitative measurement or a photographic record of the wear debris from each pair of gears will be made.

3. Bearing Check-Out

Coast-down measurements will be made on the test rigs with zero load on the test gears for determining the condition of the bearings after the test.

V. PRELIMINARY TESTS

The test apparatus for evaluating gears in laboratory atmosphere has been completely assembled and checked out. The gears used during preliminary testing were of light anodized Al alloy. The purpose of this preliminary testing was to evaluate the instrumentation and determine the accuracy of the test fixture and to obtain some idea of the quantitative measure of input torque to the test rig. No attempt was made to measure the actual time of running and wear rates during the preliminary tests. However, it should be noted that these gears started showing appreciable wear only minutes after the rig was started under 20 in.-oz. of torque and at 1800 rpm. The gears shown in Figure 4 have been run under these conditions for several hours and the wear is easily noticeable in the picture.

Before any quantitative measure of the torque input to the test rig could be made, the deflection rate of the flexible coupling had to be measured. Figure 7 shows the graph of angular deflection vs torque on one of the torque couplings. The spring used in this coupling is of the flat spiral type and the torque-deflection relation is quite linear. Knowing this relation, the actual torque measurements on the four-square test rigs were made at different loads and rpm, using the magnetic pickup as described earlier. Figure 8 shows the torque input to the test rigs after a few hours of running on the test gears. The torque was measured at several speeds up to 3600 rpm with gears under 20, 10, 5 and zero in.-oz. of load. This clearly indicated that the frictional torque increases almost proportionally to the increase in the torque load on the gears.

The master gear mechanism was also checked out. The LVDT used in conjunction with an Offner amplifier recorder system measures center distance variations with resolution better than 50 μ in. per division on the chart paper which is quite adequate for measurements of Total Composite errors and Tooth-To-Tooth Composite errors. TCE measurements on several new gears were made and the recordings conform very well to the tracings supplied by the gear manufacturer. This indicates that the accuracy of the test fixture is quite adequate for such precision measurements and no further changes in the design of the test rig is necessary.

The magnetic drive used on the system is quite adequate for the transmission of the desired torque to the test rig with little axial pull on the bearings. The separation distance between the driving and the driven magnet can be adjusted to give the desired torque coupling before the coupling will slip. In other words, a safe upper limit on the input torque can be set to automatically decouple the magnetic drive in case of sudden bearing failure or any other failure that would increase the torque beyond the set upper limit.

VI. CONCLUSIONS AND RECOMMENDATIONS

On the basis of the preliminary tests conducted after the completion of the design and construction of the test facility and instrumentation, it can be concluded that the test fixtures are performing to the desired specifications. There seems to be no necessity for any major changes in the design of the system at present. However, it might be necessary to make minor modifications in the test rig or instrumentation after the first testing is initiated. Furthermore, considering the precision tolerances maintained in building these test fixtures, we should be able to keep the bearing wear rate to a minimum and it is hoped that the bearings shall outlast the gears under the specified operating conditions.

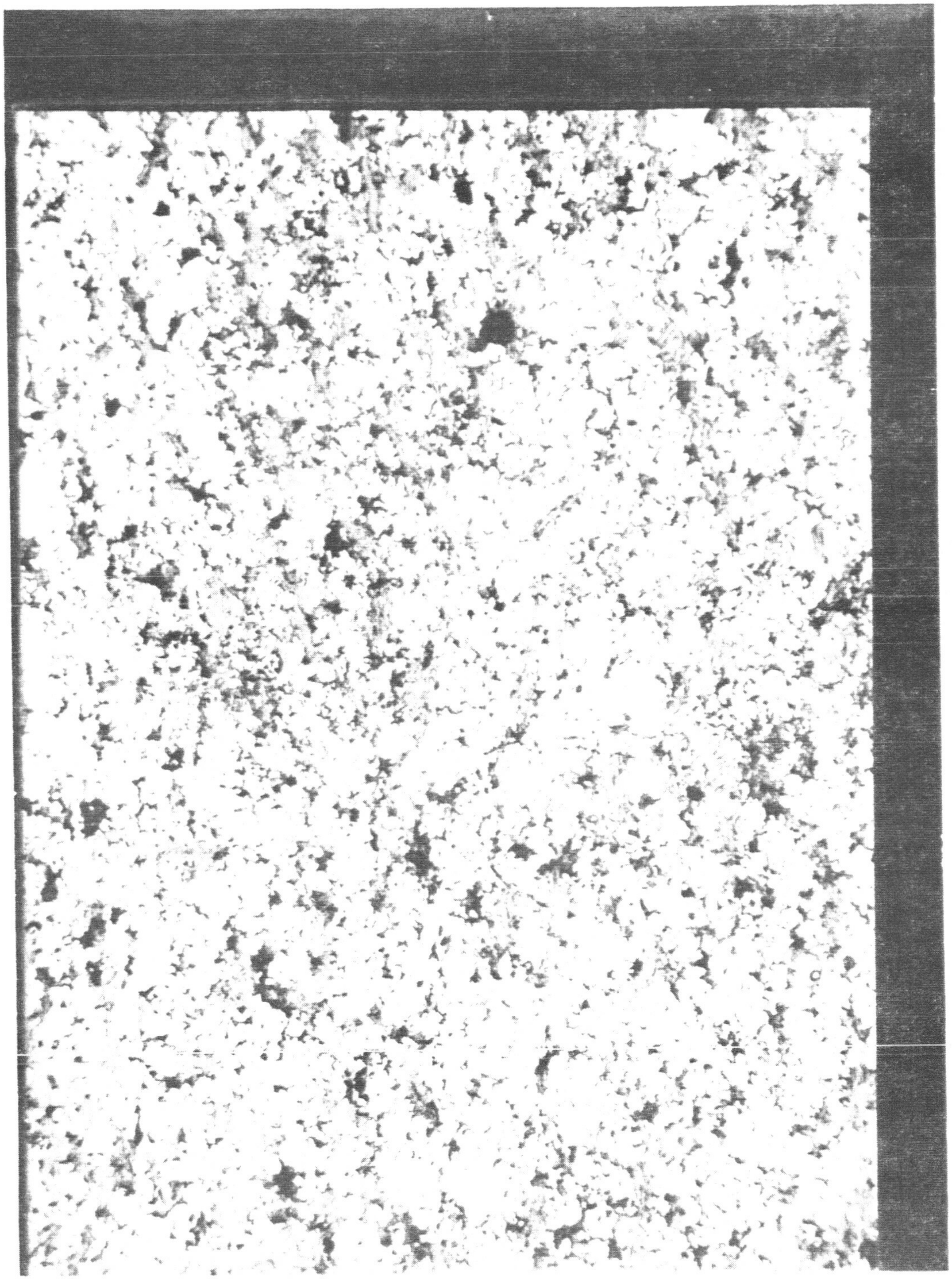

Figure 1 - Microstructure of Phosphor Bronze With MoS_2

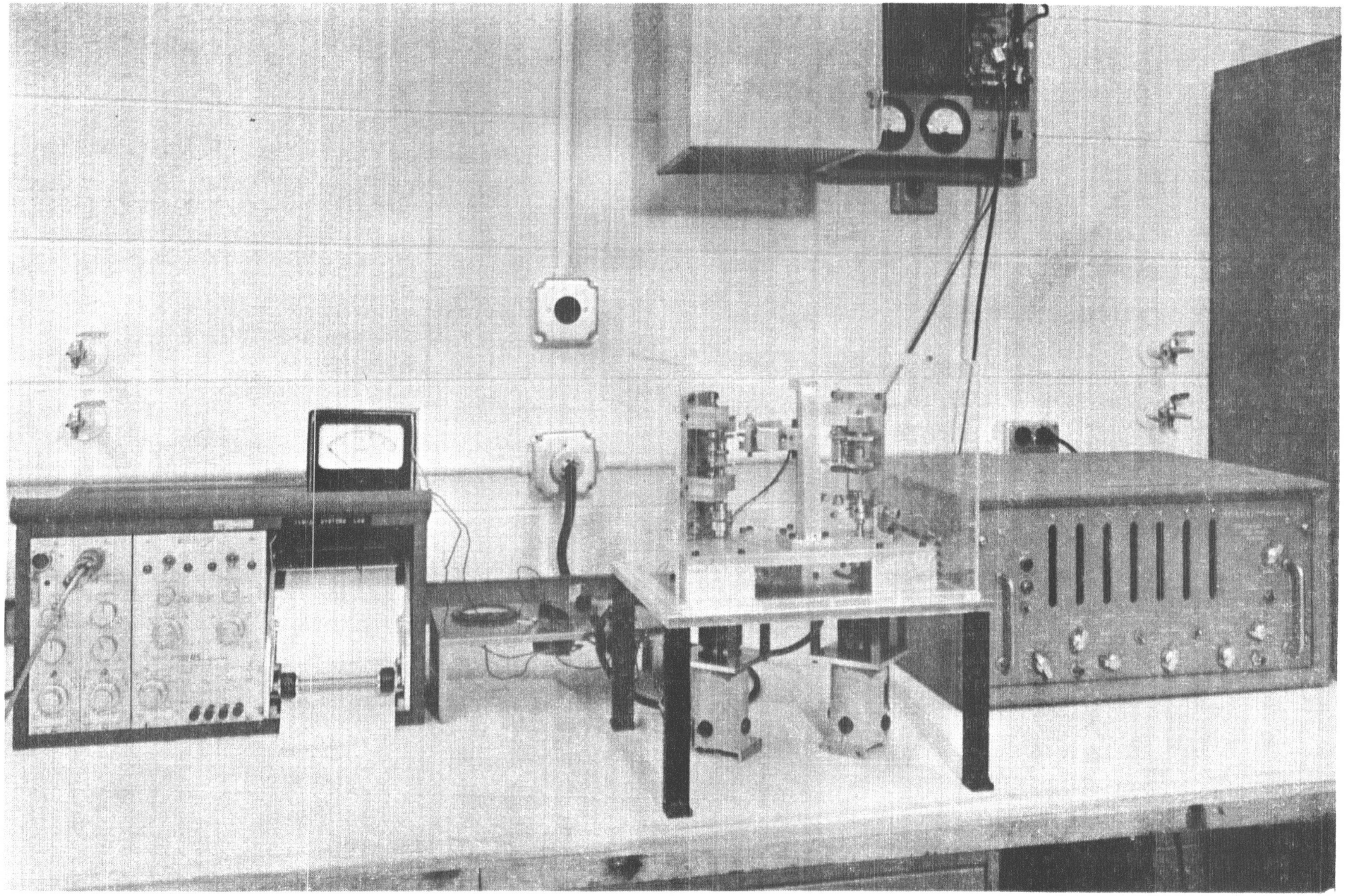

Figure 2 - Gear Test Apparatus for Laboratory Atmosphere

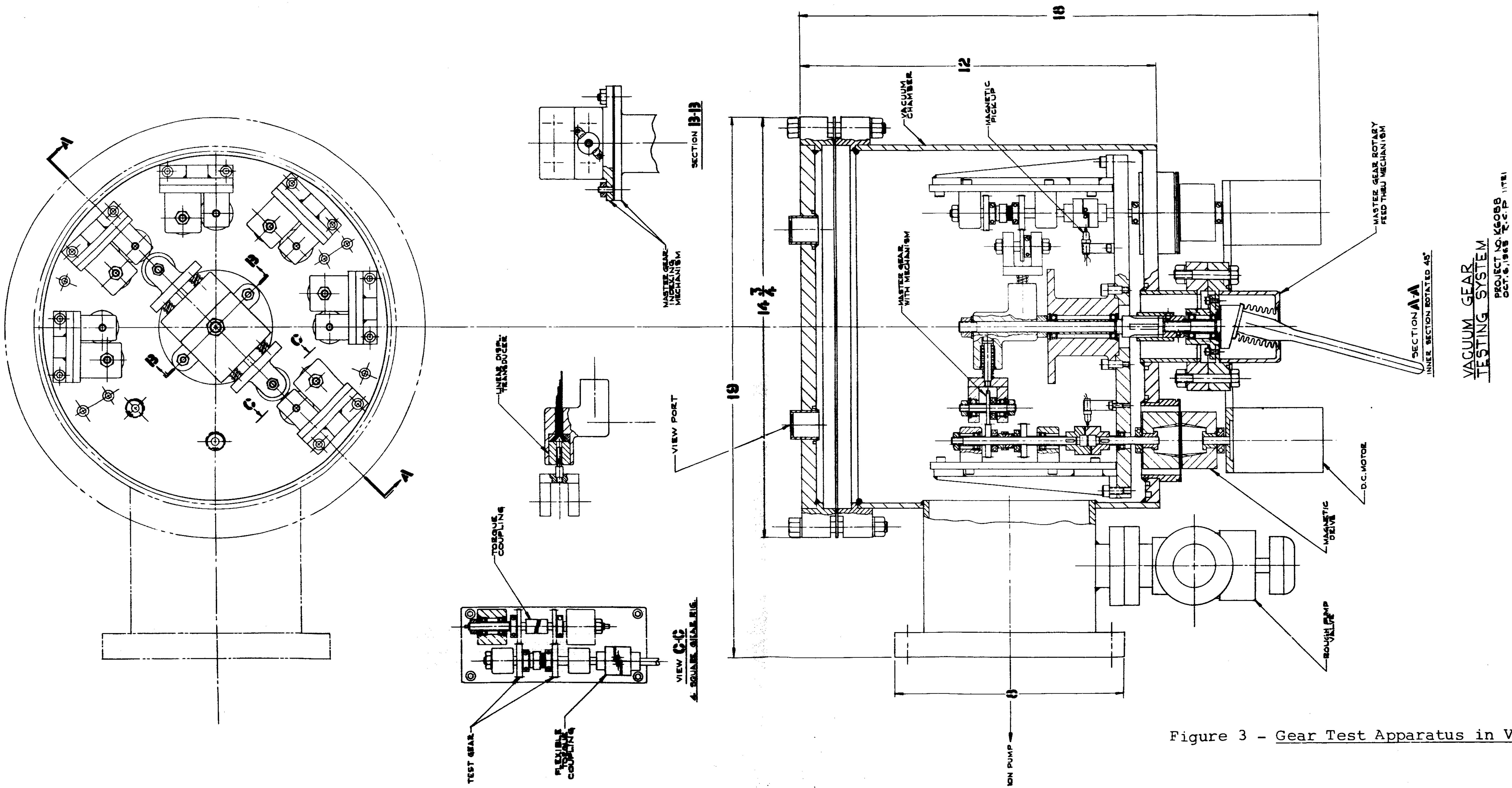

Figure 3 - Gear Test Apparatus in Vacuum

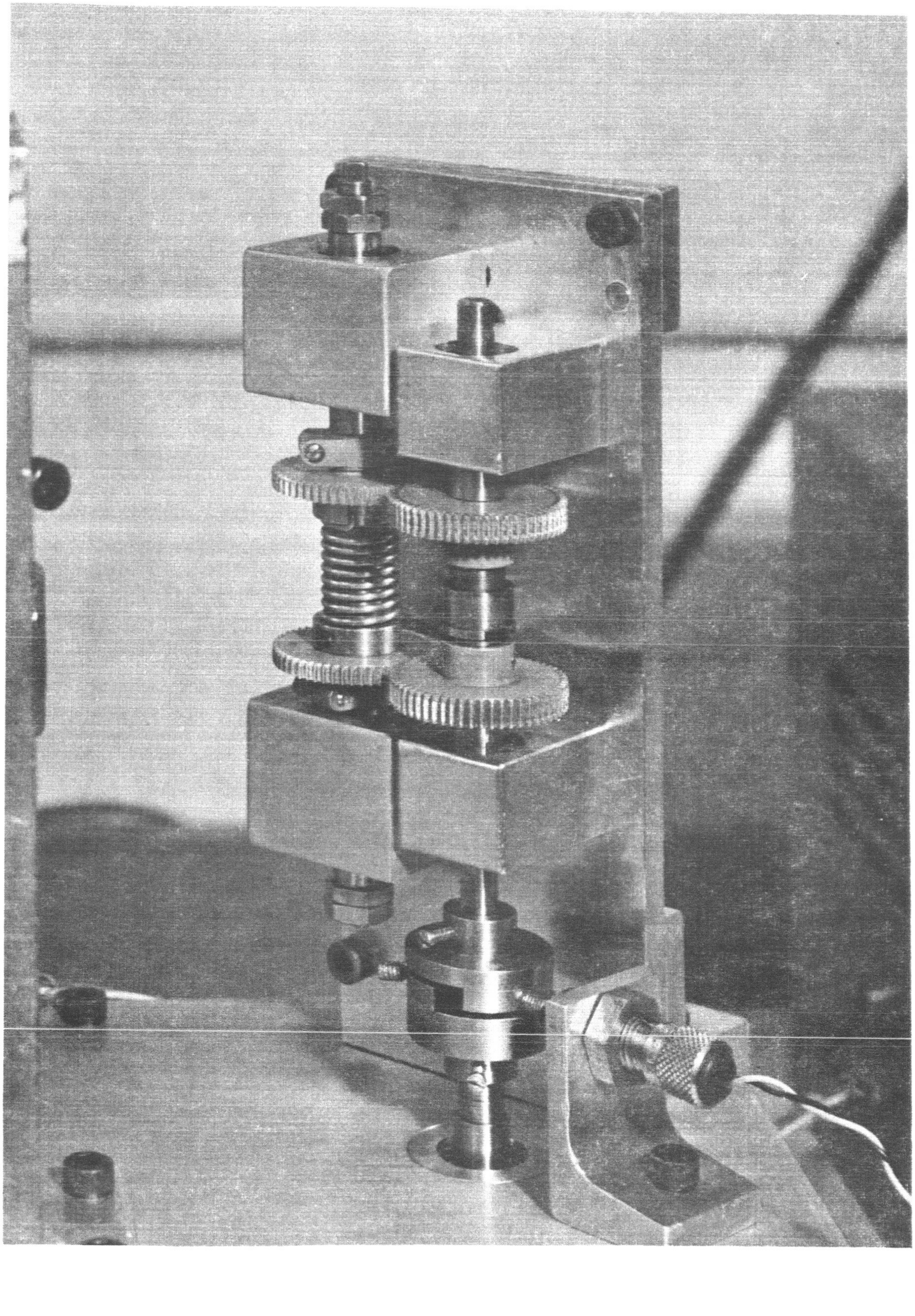

Figure 4 - Four-Square Gear Rig

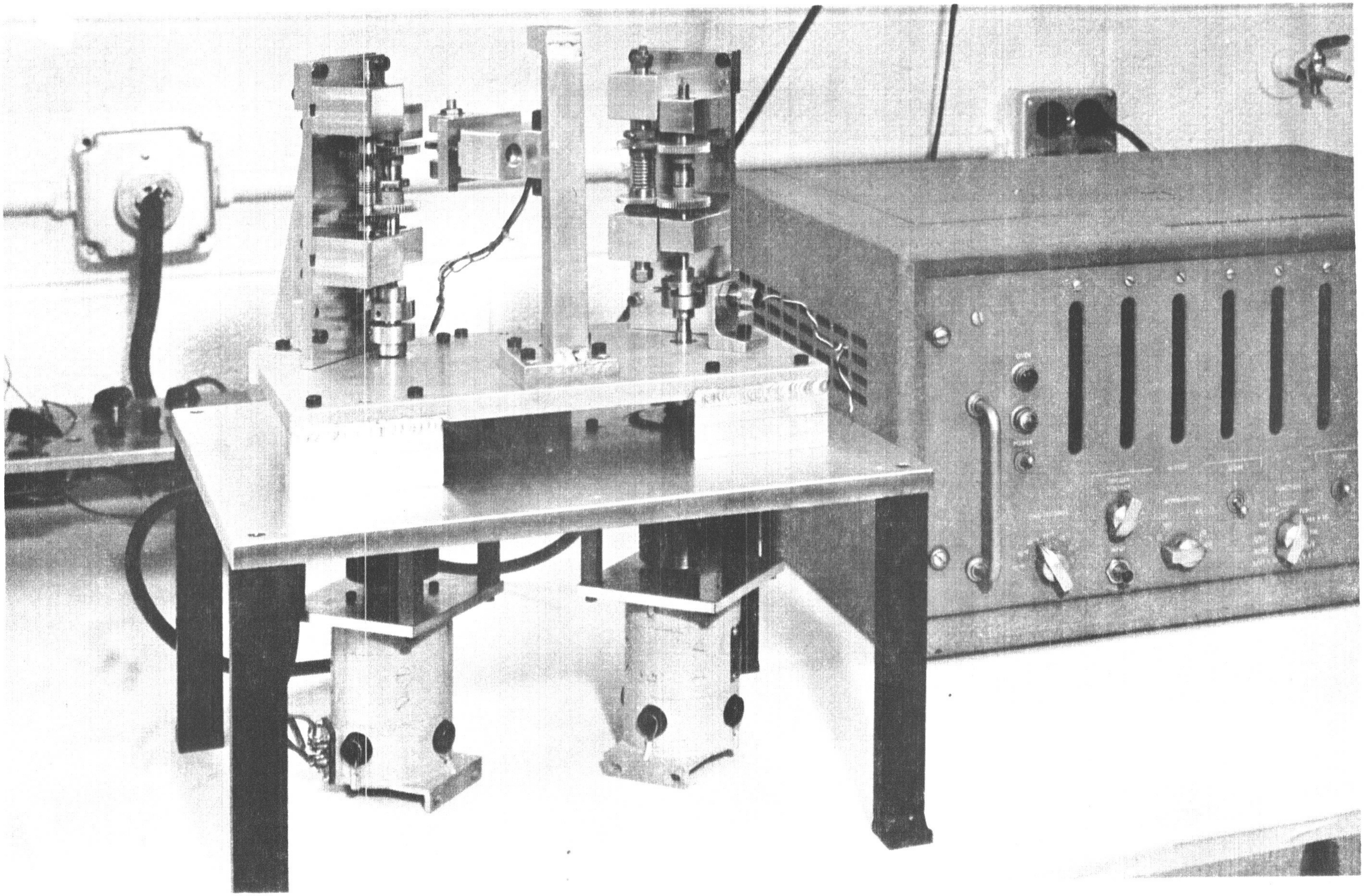

Figure 5 - Four-Square Test Rig Arrangement

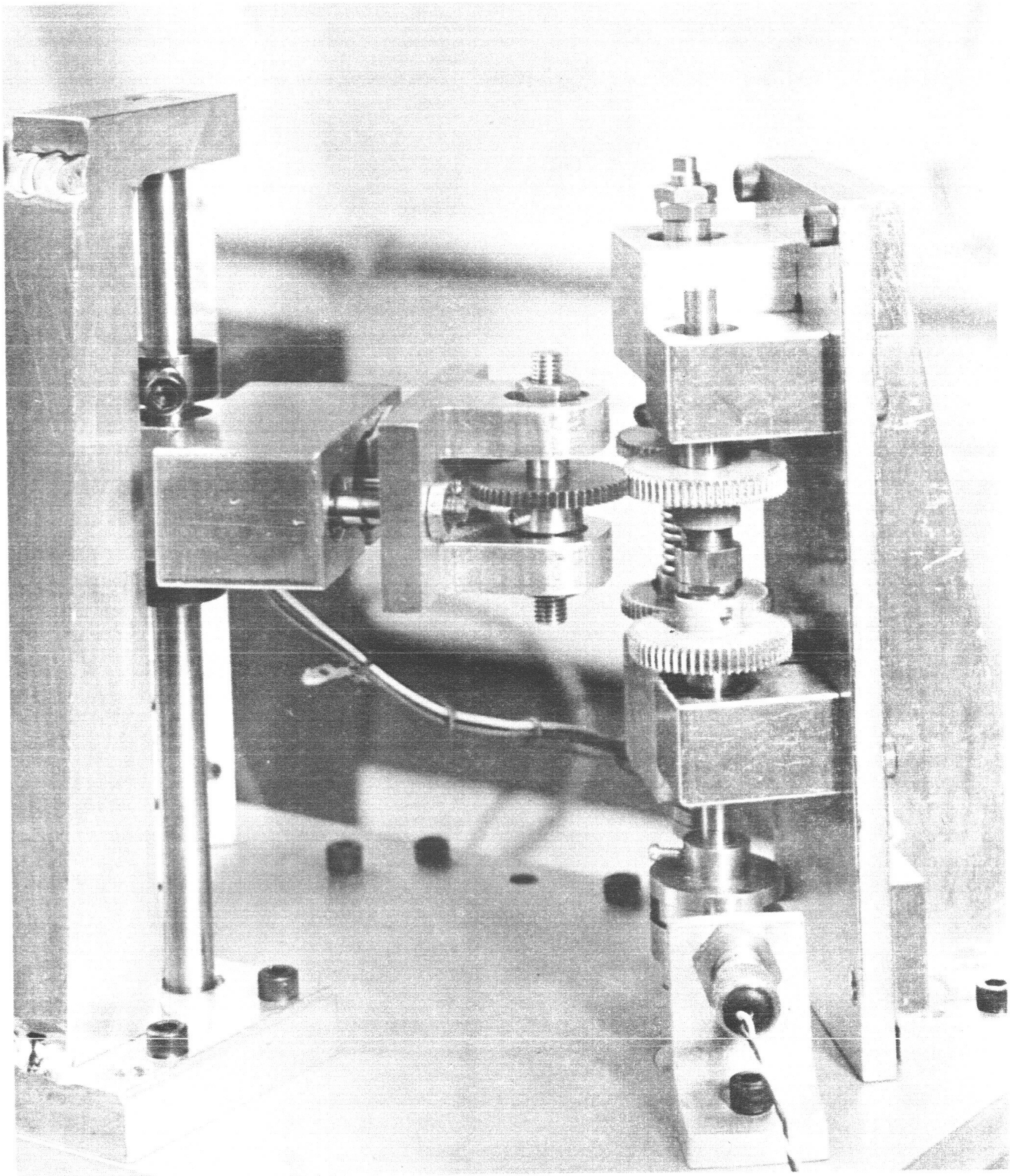

Figure 6 - Master Gear Arrangement

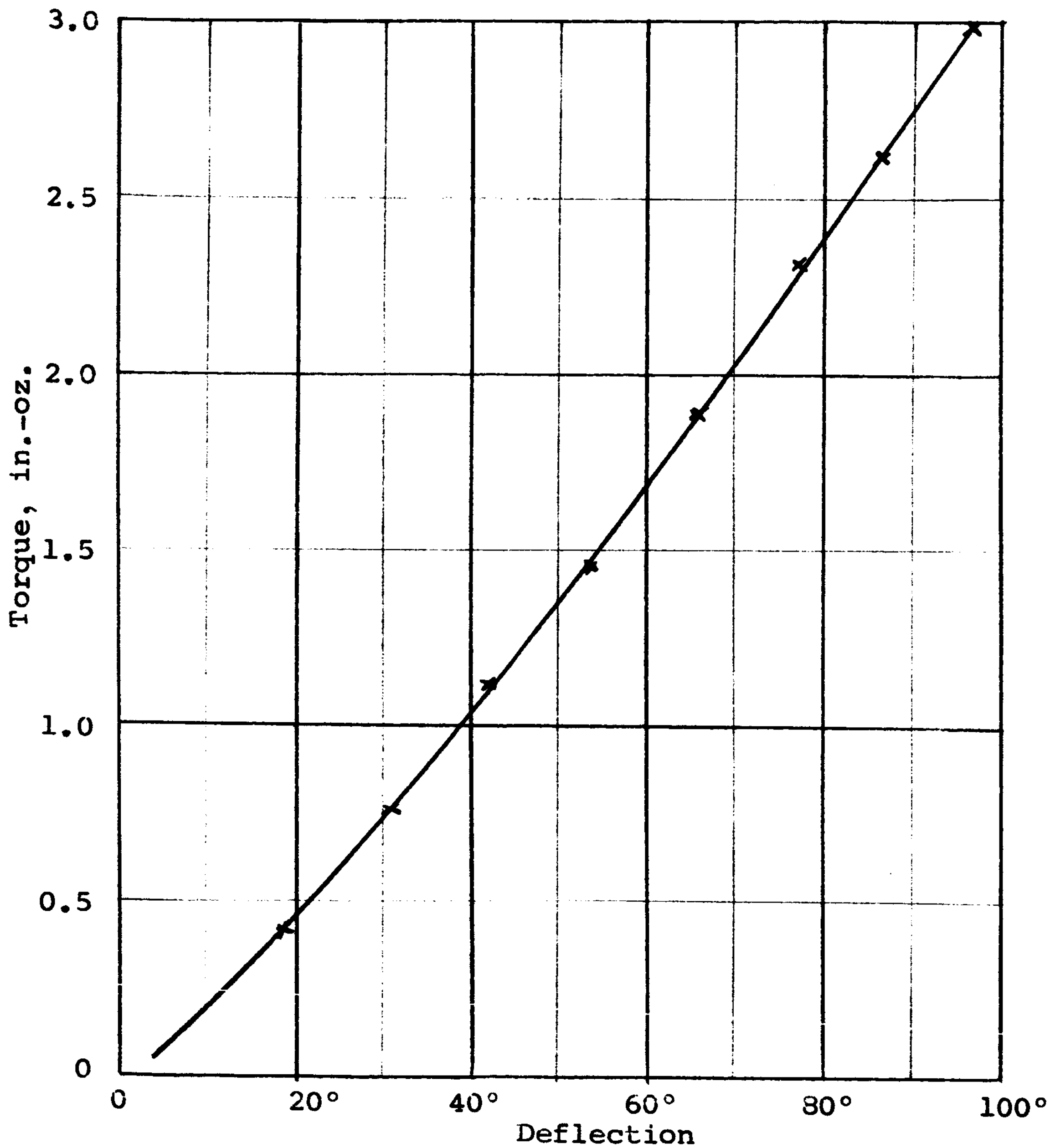

Figure 7 - Deflection Rate of Flexible Torque Coupling

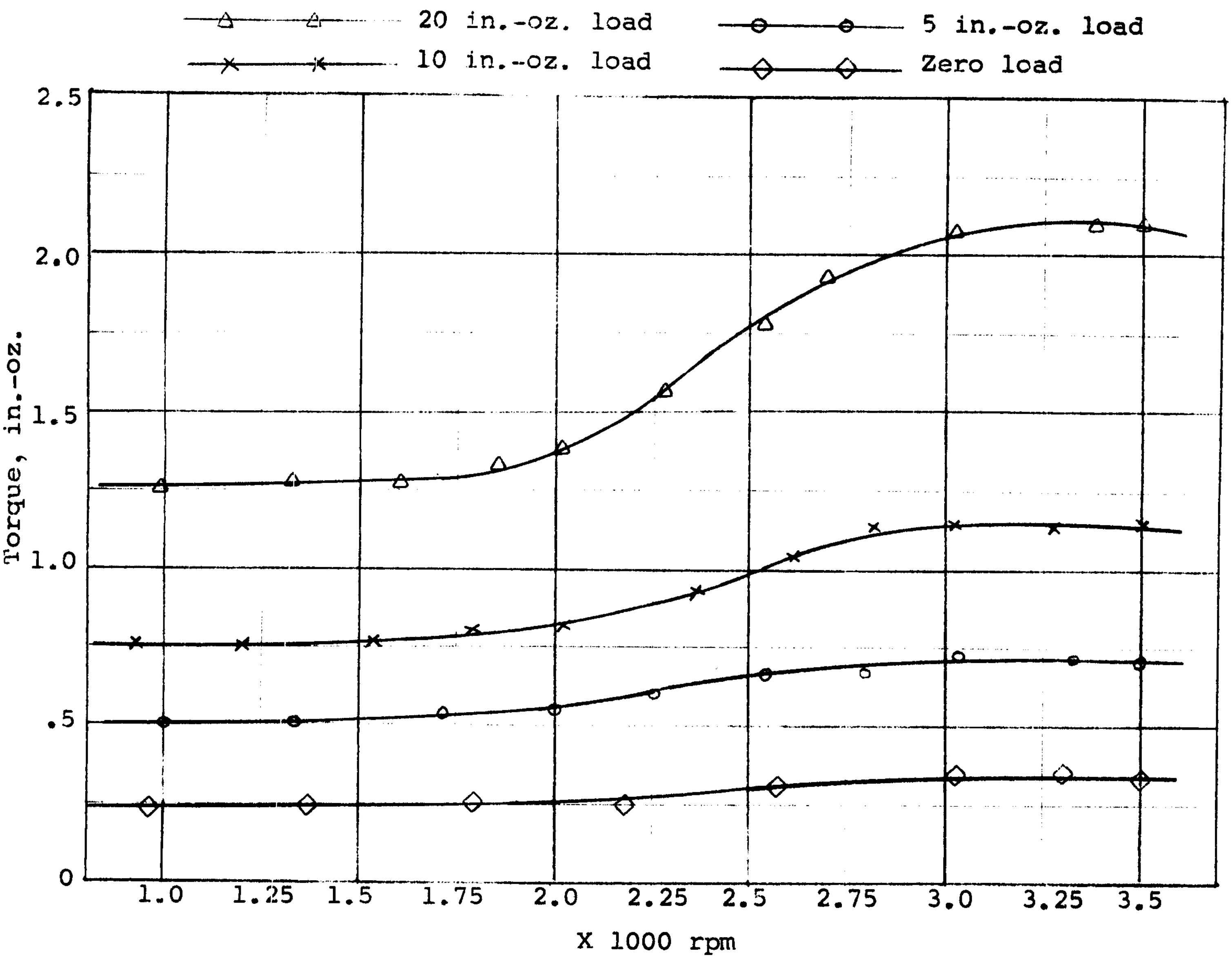

Figure 8 - Torque-Speed Relation of Test Rig